Strong constraint on dark matter – neutrino interactions via light vector bosons

Ranjan Laha,[1,2] Basudeb Dasgupta,[3,1] and John F. Beacom[1,2,4]

[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH, USA*
[2] *Department of Physics, Ohio State University, Columbus, OH, USA*
[3] *International Center for Theoretical Physics, Strada Costiera 11, I-34014, Trieste, Italy*
[4] *Department of Astronomy, Ohio State University, Columbus, OH, USA*
laha.1@osu.edu, bdasgupta@ictp.it, beacom.7@osu.edu

(Dated: April 30, 2013)

Dark matter velocity-dependent self-interactions and interactions with neutrinos mediated by a new MeV-scale vector boson V have been shown to solve all the small-scale-structure problems in a ΛCDM cosmology [van den Aarssen et al. [1]; Phys. Rev. Lett. **109**, 231301 (2012)]. We show that in the minimal version of the model such interactions with Standard Model neutrinos lead to "V-strahlung" from neutrinos in the final states of kaon and W decays, producing vastly too many missing-energy events. The minimal formulation of the proposed model is thus strongly excluded. More generally, we present new constraints on the coupling strength to neutrinos, $g_\nu \lesssim 8 \times 10^{-5}\,(m_V/\text{MeV})$, for a light vector boson of mass m_V. These model-independent constraints provide one of the most stringent bounds on additional neutrino interactions.

Introduction.— Precision measurements of the cosmic microwave background provide overwhelming evidence for dark matter (DM) as the dominant form of matter in the Universe [2–4]. These and other measurements at large distance scales are in remarkable agreement with the predictions of the Lambda Cold Dark Matter (ΛCDM) model of the Universe [5–7].

However, at the scales of galaxy clusters, galaxies, and yet smaller objects, ΛCDM predictions do not match the observations [8]. There are three important and enduring problems at small scales. *First*, "core vs. cusp" – flat cores are observed in the density profiles of dwarf galaxies, whereas numerical simulations predict sharp cusps [9–16]. *Second*, "too big to fail" – the most massive subhalos found in numerical simulations are denser than the visible subhalos of the Milky Way [17, 18]. *Third*, "missing satellites" – fewer satellite galaxies are observed than predicted in numerical simulations [19–27]. It has proven difficult to provide a solution – whether by using baryonic physics [28–36] or new particle physics [37–58] – to all three of these small-scale problems simultaneously while remaining consistent with the large-scale observations of ΛCDM.

Recently, van den Aarssen, Bringmann, and Pfrommer [1] proposed a phenomenological model of DM, described by $\mathcal{L} \supset -g_\chi \overline{\chi} \not{V} \chi - g_\nu \overline{\nu} \not{V} \nu$, that, remarkably, solves all of these small-scale structure problems. The key ingredients of this model are DM (χ) with velocity-dependent self-scattering mediated by a new MeV-scale vector boson (V) and DM scattering with neutrinos mediated by V. Velocity-dependent $\chi\chi \to \chi\chi$ scattering reduces the central densities of galaxies and their subhalos, addressing the "core vs. cusp" and the "too big to fail" problems. The $\chi\nu \to \chi\nu$ scattering ensures the late kinetic decoupling of DM, addressing the missing satellites problem by suppressing structure formation for masses smaller than $\sim 10^9 M_\odot$. The last requirement restricts the model to the parameter space shown by the shaded green region [1] in Fig. 1.

Given the importance of the tension between the ΛCDM model and observations on small scales, it is urgent to test this possible resolution. However, this is quite challenging because the only other particles whose phenomenology is affected are neutrinos (in the model of Ref. [1], Standard Model neutrinos; an extension to sterile neutrinos [1] is discussed below). We focus our attention on the neutrino interactions with V, both

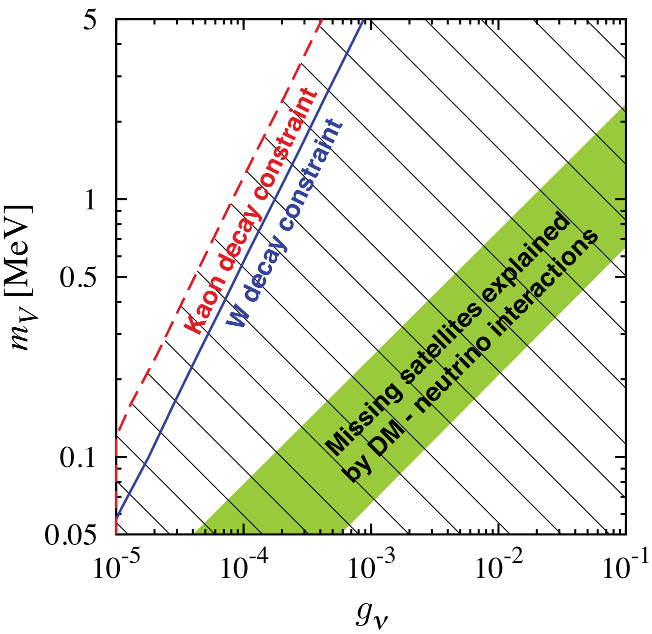

FIG. 1. Constraints on the boson mass m_V and the neutrino-boson coupling g_ν from kaon decay (dashed red) and W decay (solid blue), as derived in this work. The hashed regions are excluded at $\geq 90\%$ C.L. The shaded green region is the now-excluded parameter space of the minimal version of the model in Ref. [1] that solves the missing satellites problem of ΛCDM.

for testing this model and for developing more general constraints. Our results are shown in Fig. 1.

Extra neutrino interactions.— It is interesting to ask if neutrinos have interactions besides those due to the weak force. Neutrinos (or dark matter) may be the best particles to use when searching for new interactions, because the electromagnetic and strong forces are absent. It is hard to detect neutrinos, but sometimes sensitive tests are possible anyway.

In typical models of new interactions, including Ref. [1], it is assumed that the new bosons couple only to neutrinos, and not to the charged-lepton partners in their weak doublets, thus breaking $\mathrm{SU(2)_L}\times \mathrm{U(1)_Y}$ gauge invariance explicitly. While somewhat unnatural (see the discussion in Ref. [59]), this can be done, and is necessary to avoid strong constraints from precise measurements of charged leptons.

If neutrinos couple to new heavy bosons, this more or less just modifies the Fermi constant. However, a rich phenomenology is possible if neutrinos couple to new light bosons that are kinematically accessible. Models with a new light scalar boson coupled to neutrinos, e.g., a Majoron, have been extensively studied, and there are strong constraints on such couplings [60–76]. Interestingly, models with a new light vector boson seem to have been largely overlooked (except for Ref. [64], discussed below), which we rectify.

A light vector boson instead of a scalar is employed in Ref. [1] to enhance the neutrino cross section with dark matter; the non-zero mass prevents $1/r^2$-type forces [77]. V can typically acquire a mass via spontaneous symmetry breaking. If V is an abelian gauge boson, the Stuckelberg mechanism could also provide a mass, but in that case V would, in general, kinetically mix with photons and can be probed using a variety of experiments. Here, we concentrate on the more general scenario of a broken gauge theory.

An obvious way to constrain this model is to search for neutrinos from dark matter annihilation, but current and projected sensitivities [78–82] are not strong enough [1]. Instead, we show that it is possible to radiate bosons from final-state neutrinos in weak decays. This can turn a two-body process with a mono-energetic charged lepton into a three-body process in which the charged lepton has a continuous spectrum, indicating the presence of a new non-interacting particle to carry the missing energy. In addition, the total decay width will be increased.

For a scalar boson, the rate of boson emission scales as $\sim g_\nu^2$, where g_ν is the neutrino-boson coupling. In contrast, for a vector boson, the rate scales as $\sim g_\nu^2(E_{\rm decay}/m_V)^2$, where $E_{\rm decay}$ is the available energy and m_V is the boson mass. This enhancement factor, which arises from the longitudinal polarization modes of the light vector boson in a spontaneously broken gauge theory, greatly increases the sensitivity to the coupling g_ν (this enhancement is only possible due to the explicit breaking of Standard Model gauge invariance by coupling the V only to the neutrino [59]). We take the neutrino-V coupling to be of the $V-A$ form; our results have equal contributions from the vector and axial couplings.

Constraint from kaon decay.— Kaons dominantly decay (branching ratio $\sim 65\%$) via the 2-body leptonic channel $K^- \to \mu^-\,\overline{\nu}_\mu$, for which the muon energy spectrum is a delta function in the kaon rest frame. If a new vector boson couples to neutrinos as $g_\nu \overline{\nu}\not{V}\nu$, then there can be V-boson bremsstrahlung from the antineutrino in the final state if $m_V \lesssim 388\,\mathrm{MeV}$; the 3-body decay $K^- \to \mu^-\,\overline{\nu}_\mu V$, has a dramatically different muon spectrum [83]. Because the muon spectrum from kaon decay has been measured very precisely, we can use this to derive a strong upper limit on the probability for V emission and hence also on g_ν.

The setup of our problem is such that it satisfies all five criteria for the application of the narrow-width approximation [84], so the V is treated as an on-shell particle (it subsequently decays to $\nu\,\bar{\nu}$). We therefore consider the 3-body decay $K^- \to \mu^-\,\overline{\nu}_\mu\,V$, as shown in Fig. 2. Much of the calculation is similar to that for a related limit on parity-violating muonic forces [62]. Motivated by the model of Ref. [1], we develop new limits on general neutrino interactions.

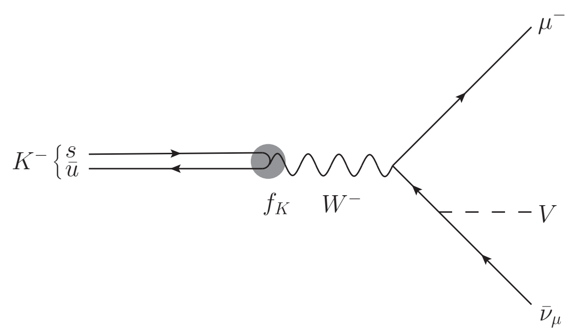

FIG. 2. Feynman diagram for $K^-(\bar{u}s)$ decay to a muon where a V is radiated from the final state antineutrino. The hadronic matrix element $\langle 0|\overline{u}\gamma^\alpha(1-\gamma_5)s|K^-\rangle = f_K\,p_K^\alpha$ is denoted by the shaded circle.

The amplitude-squared for this process, after summing over final spins, is

$$\begin{aligned}\overline{|\mathcal{M}|^2} = &\frac{4 g_\nu^2 G_F^2 f_K^2 \sin^2\theta_C}{m_V^2\,(m_V^2+2\,p_\nu\cdot p_V)^2}\times \\ &\Big[\,4\,(p_\nu\cdot p_V)^2\,(2\,p_K\cdot p_\mu\,p_K\cdot p_\nu - m_K^2\,p_\mu\cdot p_\nu) \\ &-4\,m_V^2\,p_\nu\cdot p_V\,\left\{2\,(p_K\cdot p_\mu)^2 - m_K^2(p_K\cdot p_\mu + m_\mu^2)\right\} \\ &-m_V^4(2\,p_K\cdot p_\mu\,p_K\cdot p_\nu - m_K^2\,p_\mu\cdot p_\nu)\Big]\,, \qquad (1)\end{aligned}$$

where p_i and m_i denote the 4-momentum and mass of a particle i, G_F is the Fermi coupling, θ_C is the Cabibbo angle, and f_K is related to the hadronic matrix element given in the caption of Fig. 2.

The terms are organized by powers of m_V. This is useful as m_V is smaller than all other masses in the problem. The largest contribution comes from the

term that is proportional to $1/m_V^2$, as we have verified from the full calculation. This term arises due to the sum over polarizations of the V-boson, which is $-g_{\mu\nu} + k_\mu k_\nu / m_V^2$ [59]. This polarization sum arises for a spontaneously broken gauge theory. The dependence of the decay rate on $1/m_V^2$ is similar to that of the weak boson emission process $t \to b\,W$, which scales as $1/m_W^2$ [85].

The double-differential decay rate [86] in terms of the Dalitz variables $m_{12}^2 = (p_\nu + p_V)^2$ and $m_{23}^2 = (p_\mu + p_V)^2$ is

$$d\Gamma(K^- \to \mu^- \,\overline{\nu}_\mu\, V) = \frac{1}{256\,\pi^3 m_K^3} \overline{|\mathcal{M}|^2}\, dm_{23}^2\, dm_{12}^2. \quad (2)$$

We integrate this over the allowed range of m_{23}^2, given in Eq. (40.22) of Ref. [86], to obtain the single-differential decay rate in terms of m_{12}^2. Using the relation $m_{12}^2 = m_K^2 + m_\mu^2 - 2 m_K E_\mu$, in terms of the muon total energy E_μ in the kaon rest frame, the differential rate is

$$\begin{aligned} \frac{d\Gamma}{dE_\mu} = N\, & \frac{2\sqrt{(m_V^2 - m_{12}^2)^2}}{m_V^2\,(m_{12}^2)^3} \left\{(m_{12}^2)^2 + m_V^2\, m_{12}^2 - 2\, m_V^4\right\} \\ & \times \left\{m_K^2 (m_\mu^2 + m_{12}^2) - (m_\mu^2 - m_{12}^2)^2\right\} \\ & \times \sqrt{m_K^4 - 2\, m_K^2 (m_\mu^2 + m_{12}^2) + (m_\mu^2 - m_{12}^2)^2}\,, \end{aligned} \quad (3)$$

where $N = g_\nu^2\, G_F^2 \sin^2\theta_C\, f_K^2 / (256\,\pi^3\, m_K^2)$. The main scaling of this result is $\sim g_\nu^2/m_V^2$, which means that our constraint in the (g_ν, m_V) plane will be linear.

In Fig. 3, we show the muon spectra from kaon decay in two cases: when V emission is forbidden ($K^- \to \mu^- \overline{\nu}_\mu$) and when it is allowed ($K^- \to \mu^- \overline{\nu}_\mu V$). In both cases, we plot $d\Gamma/dE_\mu$ normalized by the total (all modes) decay width $\Gamma_{\rm tot}$. For the 2-body decay, the muons have a monoenergetic spectrum with $E_\mu = 258$ MeV; we show the measured result (including energy resolution) [83] in solid blue. For the 3-body decay, the muons have a continuum spectrum; we show this in dashed red, for $g_\nu = 10^{-2}$ and $m_V = 0.5$ MeV, which are a representative set of values favored in Ref. [1]. This produces events at energies where no excess events above the Standard Model background were observed (shaded region) [87]. We also show the approximate upper limit that we derived using a flat spectrum (in the energy range used for the search) from the upper limit as presented in Ref. [87].

To obtain our constraint, we use the results from a search for missing-energy events that was reported for kaon decays with muons observed with kinetic energies from 60 MeV to 100 MeV (E_μ between 165.5 MeV and 205.5 MeV). We integrate our calculated differential decay rate, $d\Gamma/dE_\mu$, over this range of E_μ to obtain the partial decay width $\Gamma(K^- \to \mu^- \,\overline{\nu}_\mu\, V)$. The constraint on the branching ratio $\Gamma(K^- \to \mu^-$ invisible$)/\Gamma(K^- \to \mu^- \,\overline{\nu}_\mu) \leq 3.5 \times 10^{-6}$ [87] leads to the limit on g_ν shown in Fig. 1 (dashed red line). The constraint is $g_\nu \lesssim 8 \times 10^{-5}\,(m_V/\text{MeV})$ for

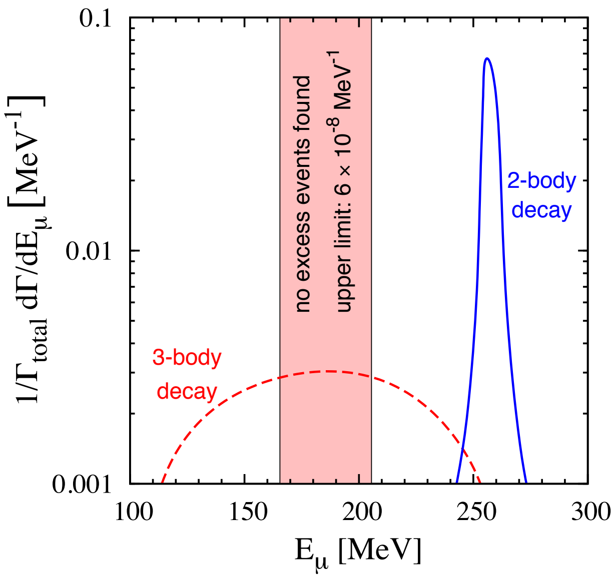

FIG. 3. Muon spectra from kaon decay for the standard 2-body decay $K^- \to \mu^- \,\overline{\nu}_\mu$ (solid blue) measured in [83] and the hypothetical 3-body decay $K^- \to \mu^- \,\overline{\nu}_\mu\, V$ (dashed red) with $g_\nu = 10^{-2}$ and $m_V = 0.5$ MeV. The shaded region shows the search region of Ref. [87], where no excess events were found. From this we derive an upper bound on the 3-body differential decay rate that is $\sim 10^5$ times lower than the dashed red line.

$m_V \lesssim 388$ MeV. This simple yet stringent constraint from kaon decay rules out the entire parameter space of Ref. [1] (shaded green region in Fig. 1). Only very low m_V values, beyond the range shown in Ref. [1] and in our Fig. 1, may survive.

This argument nominally only constrains the coupling of V to ν_μ. However, if the neutrino-V coupling is independent of the neutrino flavor, as in Ref. [1], the limit applies to all three neutrino flavors. In fact, unless there is a special connection between flavor symmetry and dark matter, this should be true for any model.

Constraint from W decay.— Our constraint can be made more robust by also considering W decay, which applies for all three flavor of neutrino and much larger values of m_V. In the following, we focus mostly on the places where there are differences from the kaon calculation. Similar considerations have been applied for electroweak bremsstrahlung in dark matter annihilation [88–90]. Our limits on general neutrino interactions are new.

In the leptonic decay of the W boson, $W^- \to \ell^- \,\overline{\nu}_\ell$ (branching ratio averaged over all three flavors $\sim 10\%$), a V boson can be emitted from the final state antineutrino, if a $g_\nu \overline{\nu} \not{V} \nu$ coupling is allowed. The 3-body decay of the W-boson (shown in Fig. 4) leads to additional events with missing energy, increasing the total decay width of the W. While this has been measured with only $\sim 1\%$ precision, the m_W^2/m_V^2 enhancement [59] leads to a comparable constraint on g_ν for an MeV-

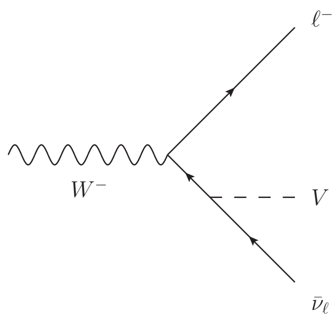

FIG. 4. Feynman diagram for W decay to leptons in which a V is radiated from the final state antineutrino.

mass V (it may be possible to develop even more stringent constraints using the charged lepton spectrum). Although $m_W/m_V \gg 1$, the decay rate can be calculated perturbatively for $g_\nu \ll 1$.

The amplitude-squared for this process, after averaging over the initial spin and summing over final spins, is

$$\begin{aligned}\overline{|\mathcal{M}|^2} = &\frac{8g_\nu^2 G_F}{3\sqrt{2}m_V^2(m_V^2+2p_\nu\cdot p_V)^2}\times\\ &\Big[4(p_\nu\cdot p_V)^2(2\,p_W\cdot p_\ell\,p_W\cdot p_\nu + m_W^2\,p_\ell\cdot p_\nu)\\ &-4m_V^2 p_\nu\cdot p_V\left\{2(p_W\cdot p_\ell)^2 - m_W^2(3p_W\cdot p_\ell - m_\ell^2)\right\}\\ &-m_V^4(2p_W\cdot p_\ell\,p_W\cdot p_\nu + m_W^2\,p_\ell\cdot p_\nu)\Big]\,. \end{aligned} \tag{4}$$

The double-differential decay width [86] in terms of the Dalitz variables $m_{12}^2=(p_\nu+p_V)^2$ and $m_{23}^2=(p_\ell+p_V)^2$ is

$$d\Gamma(W^-\to\ell^-\,\overline{\nu}_\ell\,V) = \frac{1}{256\,\pi^3\,m_W^3}\overline{|\mathcal{M}|^2}\,dm_{23}^2\,dm_{12}^2. \tag{5}$$

We integrate this over the allowed range of m_{23}^2 and also over the allowed range of m_{12}^2 to obtain the partial decay width $\Gamma(W\to\ell^-\,\overline{\nu}_\ell\,V)$. For the electron channel, this can be written as

$$\Gamma(W^-\to e^-\,\overline{\nu}_e\,V) \simeq \frac{g_\nu^2\,G_F}{384\,\sqrt{2}\pi^3}\frac{m_W^5}{m_V^2}\,. \tag{6}$$

to leading order in m_V/m_W. The width of the 2-body mode is $\Gamma(W^-\to e^-\bar{\nu}_e)\simeq G_F\,m_W^3/(6\sqrt{2}\pi)$, so the relative rate of the three-body mode to the two-body mode is $\sim g_\nu^2(M_W/m_V)^2/(64\,\pi^2)$. The factor $(M_W/m_V)^2$ allows us to probe very small values of g_ν.

The experimentally-measured total decay width of the W is 2.085 ± 0.042 GeV [86], which agrees very well with the theoretically-calculated value, 2.091 ± 0.002 GeV [86]. If the rate of "V-strahlung" were too large, then the increase in the calculated total width would be inconsistent with experiment. To obtain a one-sided 90% C.L. upper limit on the neutrino-boson coupling g_ν, we demand that $\Gamma(W^-\to\ell^-\,\overline{\nu}_\ell\,V)\le 1.28\times0.042$ GeV. The constraint is $g_\nu \lesssim 17\times10^{-5}\,(m_V/\mathrm{MeV})$ for $m_V \lesssim m_W$ and is shown by the solid blue line in Fig. 1. The constraint on g_ν is approximately the same for all three lepton flavors. As above, this rules out the parameter space of Ref. [1], and only very low values of m_V may survive. A related constraint from Z decay is weaker due to destructive interference between the two contributing Feynman diagrams.

Our constraint was derived assuming that single-V emission could be treated perturbatively. At the boundary we define, this is reasonable because the ratio of the leptonic decay width of the 3-body mode to the 2-body mode is $\sim 20\%$ (and the ratio to the total decay width of the W is $\sim 2\%$) and non-perturbative effects do not set in. To the right of our constraint in Fig. 1, this approximation will no longer be valid and the cascade emission of multiple V bosons will occur, for which non-perturbative methods must be used [59, 91]. In this region, which is still excluded, the decay rate will just grow more slowly than $\sim g_\nu^2 m_W^2/m_V^2$.

Conclusions and implications.— We present new and simple constraints on neutrino interactions with a light vector boson from the nonobservation of excess missing-energy events in the decays of kaons and W bosons. To the best of our knowledge, these are by far the most stringent constraints of this type. These model-independent constraints have a strong impact on the viability of models that make use of additional neutrino interactions.

An interesting class of such models, proposed recently in Ref. [1], uses a vector boson to couple neutrinos to DM, in order to delay the DM kinetic decoupling and to provide a natural and elegant particle physics solution to the missing-satellites problem of ΛCDM. We rule out all of the interesting parameter space of the minimal version of the DM model in Ref. [1]. This opens up again the important problem of providing a unified solution to the small-scale problems of the ΛCDM model.

Our constraints provide valuable guidance for future model building. If longitudinal modes of V are absent, these constraints are lifted. Our constraints can also be evaded if the V boson couples primarily to sterile neutrinos. However, the scattering of dark matter with neutrinos assumed in Ref. [1] would then require a large background of sterile neutrinos (or a larger g_ν) and must respect strong limits on extra light particles [2]. If active-to-sterile transformations are efficient in the early universe, they might also be in supernovae, so limits based on neutrino scattering en route could be relevant [64]. The limit from SN 1987A is weaker than ours by several orders of magnitude, but the sensitivity could be greatly increased once supernova at cosmic distances [92] are detected.

Acknowledgments.— We thank Bhubanjyoti Bhattacharya, Jo Bovy, Sheldon Campbell, Zackaria Chacko, Daniel Hernandez Diaz, Shunsaku Horiuchi, Kohta Murase, Kenny C. Y. Ng, Stuart Raby, Justin Read, Carsten Rott, Guenter Sigl, Giovanni Villadoro,

Matthew Walker, Hai-Bo Yu and especially Torsten Bringmann and Christoph Pfrommer for discussions. We thank Lisa Colarosa for help formatting Figure 1. We acknowledge the use of JaxoDraw [93] and FeynCalc [94] for Feynman diagrams and calculations, respectively. RL thanks the Aspen Center for Physics, funded by NSF Grant PHY-1066293, where a part of this work was done. RL and JFB are supported by NSF Grant PHY-1101216 awarded to JFB.

[1] L. G. van den Aarssen, T. Bringmann, and C. Pfrommer, "Is dark matter with long-range interactions a solution to all small-scale problems of Lambda CDM cosmology?", *Phys.Rev.Lett.* **109** (2012) 231301, arXiv:1205.5809.

[2] P. Ade *et al.*, "Planck 2013 results. XVI. Cosmological parameters", arXiv:1303.5076.

[3] Z. Hou, C. Reichardt, K. Story, B. Follin, R. Keisler, *et al.*, "Constraints on Cosmology from the Cosmic Microwave Background Power Spectrum of the 2500-square degree SPT-SZ Survey", arXiv:1212.6267.

[4] J. L. Sievers, R. A. Hlozek, M. R. Nolta, V. Acquaviva, G. E. Addison, *et al.*, "The Atacama Cosmology Telescope: Cosmological parameters from three seasons of data", arXiv:1301.0824.

[5] W. J. Percival *et al.*, "Baryon Acoustic Oscillations in the Sloan Digital Sky Survey Data Release 7 Galaxy Sample", *Mon.Not.Roy.Astron.Soc.* **401** (2010) 2148–2168, arXiv:0907.1660.

[6] B. A. Reid, W. J. Percival, D. J. Eisenstein, L. Verde, D. N. Spergel, *et al.*, "Cosmological Constraints from the Clustering of the Sloan Digital Sky Survey DR7 Luminous Red Galaxies", *Mon.Not.Roy.Astron.Soc.* **404** (2010) 60–85, arXiv:0907.1659.

[7] D. H. Weinberg, M. J. Mortonson, D. J. Eisenstein, C. Hirata, A. G. Riess, *et al.*, "Observational Probes of Cosmic Acceleration", arXiv:1201.2434.

[8] L. E. Strigari, "Galactic Searches for Dark Matter", arXiv:1211.7090.

[9] M. G. Walker and J. Penarrubia, "A Method for Measuring (Slopes of) the Mass Profiles of Dwarf Spheroidal Galaxies", *Astrophys.J.* **742** (2011) 20, arXiv:1108.2404.

[10] J. Penarrubia, A. Pontzen, M. G. Walker, and S. E. Koposov, "The coupling between the core/cusp and missing satellite problems", arXiv:1207.2772.

[11] M. G. Walker, "Dark Matter in the Milky Way's Dwarf Spheroidal Satellites", arXiv:1205.0311.

[12] W. de Blok, "The Core-Cusp Problem", *Adv.Astron.* **2010** (2010) 789293, arXiv:0910.3538.

[13] J. F. Navarro, A. Ludlow, V. Springel, J. Wang, M. Vogelsberger, *et al.*, "The Diversity and Similarity of Cold Dark Matter Halos", arXiv:0810.1522.

[14] S.-H. Oh, W. de Blok, E. Brinks, F. Walter, and J. Kennicutt, Robert C., "Dark and luminous matter in THINGS dwarf galaxies", arXiv:1011.0899.

[15] F. Sanchez-Salcedo, J. Reyes-Iturbide, and X. Hernandez, "An extensive study of dynamical friction in dwarf galaxies: the role of stars, dark matter, halo profiles and mond", *Mon.Not.Roy.Astron.Soc.* **370** (2006) 1829–1840, arXiv:astro-ph/0601490.

[16] M. Walker, C. Combet, J. Hinton, D. Maurin, and M. Wilkinson, "Dark matter in the classical dwarf spheroidal galaxies: a robust constraint on the astrophysical factor for gamma-ray flux calculations", *Astrophys.J.* **733** (2011) L46, arXiv:1104.0411.

[17] M. Boylan-Kolchin, J. S. Bullock, and M. Kaplinghat, "Too big to fail? The puzzling darkness of massive Milky Way subhaloes", *Mon.Not.Roy.Astron.Soc.* **415** (2011) L40, arXiv:1103.0007.

[18] M. Boylan-Kolchin, J. S. Bullock, and M. Kaplinghat, "The Milky Way's bright satellites as an apparent failure of LCDM", *Mon.Not.Roy.Astron.Soc.* **422** (2012) 1203–1218, arXiv:1111.2048.

[19] J. Zavala, Y. Jing, A. Faltenbacher, G. Yepes, Y. Hoffman, *et al.*, "The velocity function in the local environment from LCDM and LWDM constrained simulations", *Astrophys.J.* **700** (2009) 1779–1793, arXiv:0906.0585.

[20] A. A. Klypin, A. V. Kravtsov, O. Valenzuela, and F. Prada, "Where are the missing Galactic satellites?", *Astrophys.J.* **522** (1999) 82–92, arXiv:astro-ph/9901240.

[21] A. V. Kravtsov, "Dark matter substructure and dwarf galactic satellites", *Adv.Astron.* **2010** (2010) 281913, arXiv:0906.3295.

[22] B. Moore, S. Ghigna, F. Governato, G. Lake, T. R. Quinn, *et al.*, "Dark matter substructure within galactic halos", *Astrophys.J.* **524** (1999) L19–L22, arXiv:astro-ph/9907411.

[23] S. Kazantzidis, L. Mayer, C. Mastropietro, J. Diemand, J. Stadel, *et al.*, "Density profiles of cold dark matter substructure: Implications for the missing satellites problem", *Astrophys.J.* **608** (2004) 663–3679, arXiv:astro-ph/0312194.

[24] L. E. Strigari, J. S. Bullock, M. Kaplinghat, J. Diemand, M. Kuhlen, *et al.*, "Redefining the Missing Satellites Problem", *Astrophys.J.* **669** (2007) 676–683, arXiv:0704.1817.

[25] J. Wang, C. S. Frenk, J. F. Navarro, and L. Gao, "The Missing Massive Satellites of the Milky Way", arXiv:1203.4097.

[26] J. S. Bullock, A. V. Kravtsov, and D. H. Weinberg, "Hierarchical galaxy formation and substructure in the Galaxy's stellar halo", *Astrophys.J.* **548** (2001) 33–46, arXiv:astro-ph/0007295.

[27] J. S. Bullock, A. V. Kravtsov, and D. H. Weinberg, "Reionization and the abundance of galactic satellites", *Astrophys.J.* **539** (2000) 517, arXiv:astro-ph/0002214.

[28] K. Tassis, A. V. Kravtsov, and N. Y. Gnedin, "Scaling Relations of Dwarf Galaxies without Supernova-Driven Winds", *Astrophys.J.* **672** (2008) 888–903, arXiv:astro-ph/0609763.

[29] A. Pontzen and F. Governato, "How supernova feedback turns dark matter cusps into cores", arXiv:1106.0499.

[30] T. Sawala, C. Scannapieco, and S. D. White, "Formation of Isolated Dwarf Galaxies with Feedback", arXiv:0902.1754.

[31] C. A. Vera-Ciro, A. Helmi, E. Starkenburg, and M. A. Breddels, "Not too big, not too small: the dark halos of the dwarf spheroidals in the Milky Way", arXiv:1202.6061.

[32] R. Teyssier, A. Pontzen, Y. Dubois, and J. Read, "Cusp-core transformations in dwarf galaxies: observational predictions", arXiv:1206.4895.

[33] A. Zolotov, A. M. Brooks, B. Willman, F. Governato, A. Pontzen, *et al.*, "Baryons Matter: Why Luminous Satellite Galaxies Have Reduced Central Masses", *Astrophys.J.* **761** (2012) 71, arXiv:1207.0007.

[34] S. Mashchenko, H. Couchman, and J. Wadsley, "Cosmological puzzle resolved by stellar feedback in high redshift galaxies", *Nature* **442** (2006) 539, arXiv:astro-ph/0605672.

[35] S. Mashchenko, J. Wadsley, and H. Couchman, "Stellar Feedback in Dwarf Galaxy Formation", arXiv:0711.4803.

[36] J. Bovy and C. Dvorkin, "Low-mass suppression of the satellite luminosity function due to the supersonic baryon–cold-dark-matter relative velocity", arXiv:1205.2083.

[37] D. N. Spergel and P. J. Steinhardt, "Observational evidence for selfinteracting cold dark matter", *Phys.Rev.Lett.* **84** (2000) 3760–3763, arXiv:astro-ph/9909386.

[38] P. Bode, J. P. Ostriker, and N. Turok, "Halo formation in warm dark matter models", *Astrophys.J.* **556** (2001) 93–107, arXiv:astro-ph/0010389.

[39] J. J. Dalcanton and C. J. Hogan, "Halo cores and phase space densities: Observational constraints on dark matter physics and structure formation", *Astrophys.J.* **561** (2001) 35–45, arXiv:astro-ph/0004381.

[40] K. Sigurdson and M. Kamionkowski, "Charged - particle decay and suppression of small - scale power", *Phys.Rev.Lett.* **92** (2004) 171302, arXiv:astro-ph/0311486.

[41] M. Kaplinghat, "Dark matter from early decays", *Phys.Rev.* **D72** (2005) 063510, arXiv:astro-ph/0507300.

[42] M. Kaplinghat, L. Knox, and M. S. Turner, "Annihilating the cold dark matter cusp crisis", *Phys.Rev.Lett.* **85** (2000) 3335, arXiv:astro-ph/0005210.

[43] W. Hu, R. Barkana, and A. Gruzinov, "Cold and fuzzy dark matter", *Phys.Rev.Lett.* **85** (2000) 1158–1161, arXiv:astro-ph/0003365.

[44] M. Kamionkowski and A. R. Liddle, "The Dearth of halo dwarf galaxies: Is there power on short scales?", *Phys.Rev.Lett.* **84** (2000) 4525–4528, arXiv:astro-ph/9911103.

[45] A. R. Zentner and J. S. Bullock, "Inflation, cold dark matter, and the central density problem", *Phys.Rev.* **D66** (2002) 043003, arXiv:astro-ph/0205216.

[46] J. L. Feng, M. Kaplinghat, and H.-B. Yu, "Halo Shape and Relic Density Exclusions of Sommerfeld-Enhanced Dark Matter Explanations of Cosmic Ray Excesses", *Phys.Rev.Lett.* **104** (2010) 151301, arXiv:0911.0422.

[47] J. L. Feng, M. Kaplinghat, and H.-B. Yu, "Sommerfeld Enhancements for Thermal Relic Dark Matter", *Phys.Rev.* **D82** (2010) 083525, arXiv:1005.4678.

[48] M. R. Buckley and P. J. Fox, "Dark Matter Self-Interactions and Light Force Carriers", *Phys.Rev.* **D81** (2010) 083522, arXiv:0911.3898.

[49] A. Loeb and N. Weiner, "Cores in Dwarf Galaxies from Dark Matter with a Yukawa Potential", *Phys.Rev.Lett.* **106** (2011) 171302, arXiv:1011.6374.

[50] M. Vogelsberger, J. Zavala, and A. Loeb, "Subhaloes in Self-Interacting Galactic Dark Matter Haloes", *Mon.Not.Roy.Astron.Soc.* **423** (2012) 3740, arXiv:1201.5892.

[51] J. Zavala, M. Vogelsberger, and M. G. Walker, "Constraining Self-Interacting Dark Matter with the Milky Way's dwarf spheroidals", arXiv:1211.6426.

[52] S. Tulin, H.-B. Yu, and K. M. Zurek, "Resonant Dark Forces and Small Scale Structure", arXiv:1210.0900.

[53] L. Ackerman, M. R. Buckley, S. M. Carroll, and M. Kamionkowski, "Dark Matter and Dark Radiation", *Phys.Rev.* **D79** (2009) 023519, arXiv:0810.5126.

[54] J. L. Feng, M. Kaplinghat, H. Tu, and H.-B. Yu, "Hidden Charged Dark Matter", *JCAP* **0907** (2009) 004, arXiv:0905.3039.

[55] J. L. Feng, H. Tu, and H.-B. Yu, "Thermal Relics in Hidden Sectors", *JCAP* **0810** (2008) 043, arXiv:0808.2318.

[56] M. Rocha, A. H. Peter, J. S. Bullock, M. Kaplinghat, S. Garrison-Kimmel, *et al.*, "Cosmological Simulations with Self-Interacting Dark Matter I: Constant Density Cores and Substructure", arXiv:1208.3025.

[57] A. H. Peter, M. Rocha, J. S. Bullock, and M. Kaplinghat, "Cosmological Simulations with Self-Interacting Dark Matter II: Halo Shapes vs. Observations", arXiv:1208.3026.

[58] S. Tulin, H.-B. Yu, and K. M. Zurek, "Beyond Collisionless Dark Matter: Particle Physics Dynamics for Dark Matter Halo Structure", arXiv:1302.3898.

[59] P. Ciafaloni and A. Urbano, "TeV scale Dark Matter and electroweak radiative corrections", *Phys.Rev.* **D82** (2010) 043512, arXiv:1001.3950.

[60] V. D. Barger, W.-Y. Keung, and S. Pakvasa, "Majoron Emission by Neutrinos", *Phys.Rev.* **D25** (1982) 907.

[61] M. S. Bilenky, S. M. Bilenky, and A. Santamaria, "Invisible width of the Z boson and 'secret' neutrino-neutrino interactions", *Phys.Lett.* **B301** (1993) 287–291.

[62] V. Barger, C.-W. Chiang, W.-Y. Keung, and D. Marfatia, "Constraint on parity-violating muonic forces", *Phys.Rev.Lett.* **108** (2012) 081802, arXiv:1109.6652.

[63] S. Hannestad and G. Raffelt, "Constraining invisible neutrino decays with the cosmic microwave background", *Phys.Rev.* **D72** (2005) 103514, arXiv:hep-ph/0509278.

[64] E. W. Kolb and M. S. Turner, "Supernova SN 1987a and the Secret Interactions of Neutrinos", *Phys.Rev.* **D36** (1987) 2895.

[65] G. Mangano, A. Melchiorri, P. Serra, A. Cooray, and M. Kamionkowski, "Cosmological bounds on dark matter-neutrino interactions", *Phys.Rev.* **D74** (2006) 043517, arXiv:astro-ph/0606190.

[66] P. Serra, F. Zalamea, A. Cooray, G. Mangano, and A. Melchiorri, "Constraints on neutrino – dark matter interactions from cosmic microwave background and large scale structure data", *Phys.Rev.* **D81** (2010) 043507, arXiv:0911.4411.

[67] P. Fayet, D. Hooper, and G. Sigl, “Constraints on light dark matter from core-collapse supernovae”, *Phys.Rev.Lett.* **96** (2006) 211302, arXiv:hep-ph/0602169.

[68] J. F. Beacom, N. F. Bell, and S. Dodelson, “Neutrinoless universe”, *Phys.Rev.Lett.* **93** (2004) 121302, arXiv:astro-ph/0404585.

[69] Y. Farzan, “Bounds on the coupling of the Majoron to light neutrinos from supernova cooling”, *Phys.Rev.* **D67** (2003) 073015, arXiv:hep-ph/0211375.

[70] J. F. Beacom and N. F. Bell, “Do solar neutrinos decay?”, *Phys.Rev.* **D65** (2002) 113009, arXiv:hep-ph/0204111.

[71] M. Reece and L.-T. Wang, “Searching for the light dark gauge boson in GeV-scale experiments”, *JHEP* **0907** (2009) 051, arXiv:0904.1743.

[72] R. Essig, R. Harnik, J. Kaplan, and N. Toro, “Discovering New Light States at Neutrino Experiments”, *Phys.Rev.* **D82** (2010) 113008, arXiv:1008.0636.

[73] A. Rashed, M. Duraisamy, and A. Datta, “Nonstandard interactions of tau neutrino via charged Higgs and W' contributions”, *Phys. Rev. D* **87** (2013), no. 1, 013002, arXiv:1204.2023.

[74] Y. Aditya, K. J. Healey, and A. A. Petrov, “Searching for super-WIMPs in leptonic heavy meson decays”, *Phys.Lett.* **B710** (2012) 118–124, arXiv:1201.1007.

[75] C. Boehm, M. J. Dolan, and C. McCabe, “A Lower Bound on the Mass of Cold Thermal Dark Matter from Planck”, arXiv:1303.6270.

[76] T. Beranek and M. Vanderhaeghen, “Constraints on the Dark Photon Parameter Space from Leptonic Rare Kaon Decays”, *Phys.Rev.* **D87** (2013) 015024, arXiv:1209.4561.

[77] A. D. Dolgov and G. G. Raffelt, “Screening of long range leptonic forces by cosmic background neutrinos”, *Phys.Rev.* **D52** (1995) 2581–2582, arXiv:hep-ph/9503438.

[78] J. F. Beacom, N. F. Bell, and G. D. Mack, “General Upper Bound on the Dark Matter Total Annihilation Cross Section”, *Phys.Rev.Lett.* **99** (2007) 231301, arXiv:astro-ph/0608090.

[79] R. Abbasi *et al.*, “Search for Neutrinos from Annihilating Dark Matter in the Direction of the Galactic Center with the 40-String IceCube Neutrino Observatory”, arXiv:1210.3557.

[80] R. Abbasi *et al.*, “Search for Dark Matter from the Galactic Halo with the IceCube Neutrino Observatory”, *Phys.Rev.* **D84** (2011) 022004, arXiv:1101.3349.

[81] B. Dasgupta and R. Laha, “Neutrinos in IceCube/KM3NeT as probes of Dark Matter Substructures in Galaxy Clusters”, *Phys.Rev.* **D86** (2012) 093001, arXiv:1206.1322.

[82] K. Murase and J. F. Beacom, “Galaxy Clusters as Reservoirs of Heavy Dark Matter and High-Energy Cosmic Rays: Constraints from Neutrino Observations”, *JCAP* **1302** (2013) 028, arXiv:1209.0225.

[83] F. Ambrosino *et al.*, “Measurement of the absolute branching ratio for the K+ to mu+ nu(gamma) decay with the KLOE detector”, *Phys.Lett.* **B632** (2006) 76–80, arXiv:hep-ex/0509045.

[84] D. Berdine, N. Kauer, and D. Rainwater, “Breakdown of the Narrow Width Approximation for New Physics”, *Phys.Rev.Lett.* **99** (2007) 111601, arXiv:hep-ph/0703058.

[85] M. E. Peskin and D. V. Schroeder, “An Introduction to Quantum Field Theory”, Westview Press, 1995.

[86] J. Beringer *et al.*, “Review of Particle Physics (RPP)”, *Phys.Rev.* **D86** (2012) 010001.

[87] C. Pang, R. Hildebrand, G. Cable, and R. Stiening, “Search for rare k+ decays. i. k+ to mu+ nu anti-nu nu”, *Phys.Rev.* **D8** (1973) 1989–2003.

[88] M. Kachelriess and P. Serpico, “Model-independent dark matter annihilation bound from the diffuse γ ray flux”, *Phys.Rev.* **D76** (2007) 063516, arXiv:0707.0209.

[89] N. F. Bell, J. B. Dent, T. D. Jacques, and T. J. Weiler, “Electroweak Bremsstrahlung in Dark Matter Annihilation”, *Phys.Rev.* **D78** (2008) 083540, arXiv:0805.3423.

[90] M. Kachelriess, P. Serpico, and M. A. Solberg, “On the role of electroweak bremsstrahlung for indirect dark matter signatures”, *Phys.Rev.* **D80** (2009) 123533, arXiv:0911.0001.

[91] V. Berezinsky, M. Kachelriess, and S. Ostapchenko, “Electroweak jet cascading in the decay of superheavy particles”, *Phys.Rev.Lett.* **89** (2002) 171802, arXiv:hep-ph/0205218.

[92] J. F. Beacom, “The Diffuse Supernova Neutrino Background”, *Ann.Rev.Nucl.Part.Sci.* **60** (2010) 439–462, arXiv:1004.3311.

[93] D. Binosi, J. Collins, C. Kaufhold, and L. Theussl, “JaxoDraw: A Graphical user interface for drawing Feynman diagrams. Version 2.0 release notes”, *Comput.Phys.Commun.* **180** (2009) 1709–1715, arXiv:0811.4113.

[94] R. Mertig, M. Bohm, and A. Denner, “FEYN CALC: Computer algebraic calculation of Feynman amplitudes”, *Comput.Phys.Commun.* **64** (1991) 345–359.